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MAGNETIC AND DIELECTRIC AMPLIFIERS

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The most modern types of electrical amplifiers are magnetic and dielectric amplifiers, which as variable impedances are inserted in front of the existing load resistance. In the magnetic amplifier the permeability is changed by d.c. pre magnetization of the iron core and in the dielectric amplifier the dielectric constant is changed by d.c. biassing of the dielectric of a condenser. While magnetic amplifiers are chiefly suitable for the amplification of direct currents and of very low-frequency currents, capacitative amplifiers are used at high frequency voltages. Magnetic amplifiers have already won for themselves a wide field of application in general electro-technology and in regulating techniques; dielectric amplifiers, on the other hand, are in the early stages of development. There are very many characteristics which the two types of amplifier exhibit in common due to their non-linear behaviour. The magnetic amplifier, being a durable structural element, has replaced the electronic valve and the relay in many circuits and - in combination with metal rectifiers - the rotary amplifier also. Naturally, its relatively long response time sets limits to its application.

The design and development engineer is frequently faced with the problem of amplification for the purpose of power gain. This problem occurs most frequently in the sphere of control and regulation techniques because here the measurement output available is generally so small that it will not actuate the regulating member directly; hence, no solution is possible without the use of amplifiers. This amplifier must convert the given input into an output - as far as possible without distortion by making use of an auxiliary source of energy (Figure 1). The efficiency of the amplifier $\eta = G_A/G_H$ plays only a minor part in the present problem because, as a rule, the auxiliary quantity constitutes only a fraction of the total energy available.

According to the nature of the problem to be solved different types of amplifiers can be employed either singly or in combination.

Mechanical amplifiers. The lever,block and pulley, inclined plane and screw are the oldest types of mechanical amplifiers. They amplify power not energy, an example of a mechanical amplifier of energy would be a heat engine in which the applied heat energy would be the operating medium. The input quantity would be the mechanical actuation of a valve or throttle while the output would be the power delivered by the engine.

Hydraulic amplifiers. - e.g. hydraulic presses - are also power amplifiers light pressure of the hand on the valve produces greater power. Other examples of hydraulic amplifiers are hydraulic brakes on vehicles, which amplify the pressure of the foot and also oil control of machine tools. The operating medium mostly used is electrical energy which activates the oil pressure pump by means of a motor. Pneumatic amplifiers operate similarly to the hydraulic type except that the medium is air and not oil. The advantage of pneumatic control over hydraulic amplifiers lies in the shorter response period.

Electrical amplifiers are most widely used in general technology because with them it is relatively simple to convert and amplify energies. There is also an additional and considerable advantage with electrical amplifiers in that almost all measurable non-electrical quantities can be reproduced as electrical quantities and thus made capable of amplification.

Currents, voltages, and power can be selectively amplified. The process can be carried out in rotary and electromechanical amplifiers, in electronic amplifiers, and also in magnetic and dielectric amplifiers. These are known as continuous amplifiers. In addition there are the intermittent types of amplifier, (two-point amplifiers).

Electrical amplifiers. The most simple form of rotary amplifier (machine amplifier) is exemplified by the separately excited DC generator (Figure 2). This type has been known since the beginning of electrotechnology; the power is amplified 10 to 50 times according to the size of the generator. By connecting two generators in tandem - for example the auxiliary exciter and the exciter of a turbogenerator installation- it is possible to increase the amplification of power to very high values. The machine amplifier has reached a special stage in the Leonard generators in which the dynamo drives a motor with a speed which can be varied at will. The most recent form of the machine amplifier is the transverse field machine (amplidyne) which is being used to an increasing extent in the techniques of speed control and regulation.

Electromechanical amplifiers are employed in the form of drum regulators, vibration regulators (Tirrill regulators) and carbon pile voltage regulators.

Electronic amplifiers are chiefly electronic valves and gas-filled tubes which since the discovery of the control grid have been used to the widest extent - one has only to remember the millions of wireless sets - in electrotechnology. By controlling the valve with a grid potential (Figures 3 and 4) it is possible to vary the magnitude of the output without inertia. Electronic amplifiers can be voltage or current amplifiers. The control of larger powers is principally the function of thyratrons and grid-controlled mercury vapour rectifiers (Figure 4).

Magnetic amplifiers (Figure 5), also called amplistats or transductors operate with d.c. magnetic biassed reactors. In this type the inductive resistance of a saturable reactor is varied. Their chief function is that of current amplification; the output current is generally an alternating current but by connecting a metal rectifier to the output, this can be converted into direct current.

Dielectric amplifiers.* (Figure 6), in common with the magnetic amplifiers, depend on variation of impedance. This impedance, in the capacitative amplifiers, is a biassed condenser with a non-linear capacity curve. They are used principally as voltage amplifiers for the higher frequencies.

Intermittent amplifiers have been known for many years in the sphere of control as relays and protective devices. Of course, as amplifiers they have the distinct disadvantage that they can only be adjusted in two positions: they can only be open ($G_A = 0$) or closed (G_A is a maximum).

Magnetic Amplifiers

Fundamental Principles

If it is required to vary the current in a load resistance connected to a constant voltage, the usual procedure is to connect a variable resistance in front of the load resistance R_A. This is sometimes accompanied however by considerable power consumption in the regulating resistance; moreover the control of fairly high current intensities creates difficulties because as the current intensity increases the sliding contacts are subjected to stresses which become increasingly difficult to withstand. In A.C. circuits the solution of the problem is made easier by the fact that the variable resistance is generally a low loss A.C. impedance. In the magnetic amplifier the variable impedance is inductive and is calculated from:

$$Z = \omega L = 2\pi f k \mu = \text{const}\ \mu \quad . \ . \ . \ . \ . \ . \ . \ . \quad (1)$$

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* The technical world has as yet no unform expression for an amplifier with variable dielectric; the term capacitative amplifier is also frequently met with.

where: Z is the A.C. impedance, ω the supply frequency, L the inductance, f the frequency of the alternating voltage, k the form factor of the inductivity, and μ the permeability of the core.

The impedance is thus in direct proportion to the permeability; the process is based on the fact that, by A.C. polarization, the permeability can be reduced from its initial basic value [2,4,5,9,10] **

In its simplest form the magnetic amplifier consists of a saturable iron core with two windings; the normal A.C. winding (power section) and, wound over this, the A.C. control winding (control section). In Figure 5 these two windings are shown separately, side by side. In practice such a biassed reactor has to be fitted with a non-saturable reactor for the A.C. control circuit (as in Figure 5) in order to suppress the voltages induced in the D.C. winding from the A.C. winding due to the transformer effect. The magnetization produced in the biassed reactor will then be determined by the steady D.C. control current.

In Figure 7 all the terms used in the following formulae for voltages, currents, etc. of the magnetic amplifier have been assembled so that the general terms (G_E ...) in Figure 5 can be transposed immediately into the usual practical nomenclature (i_E ...)* . Using Figure 7 an explanation will now be given of the electrical processes in the magnetic amplifier. Let it first be assumed that no D.C. is flowing in the control winding ($i_E = 0$) and that $R_A = 0$. If the magnetization curve of the saturable coil has the form illustrated in Figure 8 (transformer sheet IV), the sinusoidal potential U across the reactor develops a current i_A which is also sinusoidal, since the magnetization curve is practically linear in this zone.

If a direct current i_E flows through the control winding the working point A_1 of the alternating potential is shifted from the zero point of the magnetization curve to the working point A_2 (Figure 9). By this shifting of the working point from A_1 to A_2 a section of the magnetization curve is reached where it is no longer linear. The current-time area of the current which now develops (i_A), i.e. the enclosed area in the diagram, is larger than in the case of magnetic bias. A similar process can be found in the case of electronic valves where the valve characteristic $J_a = f(U_a)$ depends on the grid potential.

* The circuit symbols for magnetic amplifiers have not yet been standardised. The control coils are often drawn at right angles to the A.C. windings.

** For references see end.

If the D.C. polarization is increased still more and the working point A_3 is reached (Figure 10) the positive alternating potential amplitude enters the zone of saturation and an alternating current develops which has an effective value markedly greater than without magnetic bias. The essential characteristic of a magnetic amplifier is it's non-linearity.

Examination of Figure 10 might indicate that some rectification of the alternating current had set in, since the current no longer produces equal areas about the zero line. This does not happen, however, because in reality, with A.C. excitation the magnetization curve forms a hysteresis loop; for purposes of simplification this has not been shown. If the alternating potential is reflected at this hysteresis loop the working point A_3 moves further down, causing the current to become symmetrical about the zero line and also, in this case, to fulfil the condition for alternating current

$$\int_0^{2\pi} i \, dt = 0.$$

From the magnetization curve of the core material it is easy to derive by differentiation the function $\mu = f(i_E)$, since $\mu = dB/dH$. Of course this differential does not apply quite strictly in the transition zone in the case of small control currents i_E. Figure 11 shows the course of the permeability and hence also of the reactor inductivity L in relation to the bias current i_E . The steeper the initial slope of the magnetization curve and the more definite the saturation hump, the more effective is the operation of a magnetically biassed choking coil. For this reason core materials having almost rectangular magnetisation curves hysteresis loops are employed for high performance magnetic amplifiers.

Starting with the basic pattern of the biassed reactor, use has already been made of the single-phase magnetic amplifier, because the simple biassed reactor had the definite drawback that the control circuit had to be provided with a reactor and the resulting alternating current was not symmetrical about the zero line. These drawbacks are removed by a magnetic amplifier with two A.C. windings, (Figures 12-14). Figure 12 shows a normal iron-clad core in which each outer leg is wound with an A.C. winding. These two A.C. windings are in parallel and lie in series with the load resistance R_A. The applied alternating voltage E induces the fluxes Φ_1 and Φ_2 in the outer legs. In the middle leg the two fluxes are

opposed to each other in direction and, since they are equal in magnitude, cancel out. Thus, in the winding on the middle leg, no alternating potential can be induced on the fundamental wave. Since the two A.C. windings are in parallel, the harmonics which develop are also suppressed. There is no need, therefore, in this magnetic amplifier, for a smoothing choke in the D.C.-control circuit; and the output current is symmetrical about the zero line. The best core material for such a lamination is dynamo sheet iron because, owing to the dissipation at the intersections of the laminations the magnetization curve for high-grade core laminations is not distinctly rectangular. On the other hand, for fairly high duty, it is best to use the transformer construction of the ideal type, i.e. an annular core, so that there is practically no dissipation. In this case a circuit like the one shown in Figure 13 is employed. The magnetic fluxes Φ_1 and Φ_2 are again so directed that the induced fundamental waves cancel out in the control winding. The core materials used here are highly permeable annular sheets having permeability values up to 100,000. The circular core amplifiers are more expensive than iron-clad core amplifiers, of course, because owing to the difficulty of the ring winding process the proportion of costs for wages is about twice that for materials, while it is roughly the other way about for amplifiers with transformer laminations.

Figure 14 shows types of single-phase magnetic amplifiers. In contrast to the arrangement described above with one core the middle leg of each core of the left hand amplifier (with two iron-clad cores M 102b) is wound with an A.C. winding ("a" in Figure 14), while the common control winding surrounds both cores. The annular-core amplifier('b', Figure 14) has two cores made of the material 5000 Z * . To simplify production of two cores which each have an A.C. winding are surrounded theone control winding, an arrangement frequently met with in practice. Single-phase magnetic amplifiers with dynamo laminations are produced commercially up to about 4 kVA, and with high-permeability annular cores up to about 400 VA rated capacity.

If the powers which has to be controlled is higher than these it is advisable to use three-phase magnetic amplifiers because of the more uniform mains loading. This can be done either by the suitable connection of three single-phase magnetic amplifiers or specially constructed three-phase amplifiers can be used (cf. e.g. Figure 18). This is built up from three single cores currounded by a common control winding. These large amplifiers are constructed on the same lines as ordinary transformers.

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* 5,000 Z a core-material produced by the Vacuumschmelze A.G. Hanau, is a nickel-iron alloy of high permeability. In these annular cores the core is coiled like ribbon. Other materials for magnetic ring-core amplifiers are Mu metal, Permalloy C, and Hyperm 50.

The magnetic amplifier is essentially an A.C. amplifier which is controlled by direct current. However, if D.C. is required in the output circuit, the alternating output current can be converted into direct current by the insertion of a full-wave rectifier circuit arrangment of metal rectifiers. The current amplification rate is obtained from the ratio of the arithmetic mean of the D.C. output to the required control current; it can amount to 1 : 330. On the other hand the factor N_A/N_E is the power amplification rate which, in the case of magnetic one-stage amplifiers may reach 100,000. It is possible, by series connection of magnetic amplifiers, to increase the amplification very considerably; the total amplification is obtained from the product of the single amplification rates.

As with all amplifiers the degree of amplification can be substantially increased by feedback coupling. Since the magnetic amplifier is a current amplifier, this feedback must be a current feedback, i.e. the output current is led back to the amplifier after rectification by a separate feedback winding, so that an auxiliary bias magnetization is produced, which is dependent upon the output current. Very high degrees of amplification can be achieved by this means. Since, in contrast to the electronic amplifiers, every magnetic circuit has a natural inertia - the magnetic field has to be built up and to die away - a response time is associated with magnetic amplifiers and this can be measured. The response time is the time required, if there is a sudden change of control current from zero up to the maximum value, to change the output current from 10% to 90% of its maximum; it is roughly proportional to the current amplification rate and inversely proportional to the supply frequency. The response time can amount to some seconds in the case of the amplification rates mentioned above, but it usually fluctuates between 0.05 and 0.3 seconds with a supply frequency of 50 c.p.s. If several amplifiers are connected in series the response times are added together but the amplification rates are multiplied; it is therefore possible to reduce the response times by appropriate circuits. Another possibility for reducing the response time is the employment of high-resistance control circuits and also the application of higher supply frequencies.

In making calculations for magnetic amplifiers an important fact is that amplifiers which are not back-coupled behave like current transformers, i.e., the current flow in the control and power sections are equal. Of course in this case the arithmetic mean of the current has to be substituted for the power section. It appears, that the current amplification rate of an amplifier without feedback coupling is dependent only upon the transformation ratio of the number of turns (control winding to A.C. winding); for this reason it can be calculated exactly in advance.

Applications

One of the most important fields of application for magnetic amplifiers is in the technology of speed control. The ideal variable speed electric motor is the D.C. shunt-wound motor, the speed of which can be controlled from zero up to the maximum by varying the armature voltage. In addition the rotation speed can be raised still further by reducing the field strength (where the torque is fairly small). If a magnetic amplifier connected to an A.C. mains supplies the armature of a D.C. shunt-wound motor through half-wave rectifiers - a combination often referred to as "reactor regulated drive"[7] the armature voltage of the motor and hence also its rotation speed can be varied very simply by magnetic bias of the magnetic amplifier. This control by the amplifier is not enough by itself, because, owing to the drop in potential in the reactor, half-wave rectifier, and armature, there is a pronounced reduction in rotation speed with load, i.e. as the torque of the motor increases. The rotation speed must therefore be regulated, i.e. the rotation must be measured and compared with a constant theoretical value. The difference between the theoretical and actual values acts on the amplifier as an increase in the armature voltage when the load increases. In the case of high performance speed regulators the actual value is obtained by means of a tachometer-dynamo, the output voltage of which is in proportion to the rotation speed. On the other hand, if a drop in speed of several per cent between no-load and full-load conditions is permissible a circuit, such as that shown in Figure 15 is employed. The magnetic amplifier - with economy feedback connected for self-saturation and with D.C. output connected to a converted Graetz-circuit - is loaded by the armature of a D.C. shunt-wound motor. The armature voltage U_{actual} - which is approximately proportional to the rotation speed - is compared with an adjusted D.C. voltage $U_{theor.}$ If, as the result of increased load, the speed of the motor is reduced, there is also a drop in the terminal voltage of the motor. The difference between the two voltages U_{theor} and $U_{act.}$ generates a current through the bias winding 'c' of the magnetic amplifier; this current is such that the armature voltage of the motor is increased until the equality of the voltages $U_{theor.}$ and $U_{act.}$ has been restored. Since, however, the rotation speed of the motor is not directly proportional to the armature voltage, because the decrease in speed consequent upon the drop in armature voltage is still effective, the voltage drop is compounded with the aid of the reaction winding 'd' (Figure 15). If there is constant field excitation of the motor this circuit permits a speed variation of 1 : 25 where amplifiers with dynamo laminations are employed. For small motor powers annular core amplifiers with highly permeable sheet iron are used and in this case the adjustable speed range can be brought up to 1 : 100.

The rotation speed curves $n = f(M_d)$ for the reactor coupled speed regulator can be seen in Figure 16. For comparison with the regulated curves 'b' the dotted lines show the rotation speed curves 'a' for a controlled D.C. shunt-wound motor connected directly to the D.C. mains. Normally such a motor has a speed range of only about 1 : 10 because, owing to the natural 10% speed drop between no-load and full-load, it would stop if it ran at an adjusted speed of 10% of the nominal value below full-load. These limits can be substantially widened by regulation through a magnetic amplifier.

Reactor-coupled speed regulators with single-phase connection to the A.C. mains supply are produced for motor outputs up to 2 kW; and with three-phase A.C. connection up to 8 kW. These regulators have proved very satisfactory for machine tools, testing machines, and in fuel regulation for power station steam generators. They have also been used with good results for small servo-motors.

At higher outputs, magnetic amplifiers, in combination with half-wave rectifiers, have begun to be used for the field excitation of motors and generators. Thus, for example, the auxiliary exciter of a turbo-generator installation can be used more economically if a magnetic amplifier is fitted. If a magnetic amplifier is employed for field excitation in a rolling-mill motor the field voltage can be varied with low regulation consumption.

For voltage regulation in small and medium three-phase current generators [6] magnetic amplifiers are installed as contactless regulators. These voltage regulators with magnetic amplifiers are distinguished - in contrast to vibrating regulators - by the fact that they are not sensitive to position or vibration, particularly in non-stationary generating plant. The potential of the three-phase current generator is kept constant at ±1%, independent of the load and the power factor.

Rectifier technology offers a wide field of application for magnetic amplifiers [1] where they are used as regulators and variable-gain amplifiers. Rectifiers regulated by means of magnetic amplifiers are especially useful in low-performance operations where the regulation required does not make such great demands. Charging rectifiers with magnetic amplifier regulation are used especially for large storage batteries on the rail motor cars of the German Federal Railways; with these it is possible to charge the lead storage batteries without electronic tubes and relays on an economic scale. In addition by means of rectifiers with magnetic regulating amplifiers, the batteries can be charged again without trouble on the principle of three-stage charging, when the driving current has discharged them completely.

Magnetic amplifiers can be employed as inductive series resistances for thermostatically regulated heating of fairly small

industrial resistance furnaces (Figures 17 and 18). The temperature is measured by a thermo-element or resistance thermometer and then converted into a proportionate current (actual value of the temperature). This temperature is compared with a theoretical value for the temperature and the difference between the two currents is fed to a magnetic preamplifier as a D.C. control current. This preamplifier is necessary as it is not possible to control the power amplifier with the small amount of energy available. The output current from the preamplifier then flows into the three-phase power amplifier as a control current.

Illumination is one of the latest fields in which magnetic amplifiers have been used. Here they operate as compensating resistances for filament lamps and fluorescent tubes and make it possible to vary the luminous intensity of these light sources. This can simplify many problems of lighting; for instance the control elements for 200 filament lamps in a theatre can be accommodated on a switch panel only 2 m^2 in size. The electrician can therefore control the individual lamp circuits with ease and certainty by adjusting small variable resistances.

In the technology of telecommunication, measuring control, and regulation [8] low power magnetic amplifiers have been used for about 15 years. Even though there has been no success from attempts to amplify telephone alternating currents by magnetic means - if there were, overseas telephony by cables would be possible - A.D.C. transformer developed by Kramer [3] has nevertheless been in use for D.C. measuring techniques for a long time; these are produced up to a transformation ratio of 1 : 80,000 with an output current of 5A with a class accuracy of ± 0.5%. These D.C. transformers have the same electrical construction as magnetic amplifiers with series-connection of the A.C. windings. The only difference between them is the transformation ratio. While the amplifiers amplify currents, D.C. transformers transform large currents into small ones. For this reason D.C. transformers mostly have only one control winding in the form of a bar pushed through the coils and carrying the current to be measured. Magnetic amplifiers are also in common use for controlling magnetic powder couplings, as amplifiers for photoelectric cells, and as magnetic current stabilizers for regulating purposes.

The largest magnetic amplifier units are those designed for long-distance circuits. Units of up to 50 MVA are to be installed alongside the big long-distance lines so as to compensate the capacitative idle current of the lines. The compensation is automatically regulated by a grid-controlled rectifier which supplies the biassing current.

Dielectric Amplifiers

The dielectric amplifier resembles the magnetic amplifier in that, as a (capacitative) compensating resistance it is

controlled by way of a D.C. voltage (connected to the condenser); here, too, an alternating voltage is employed as an auxiliary quantity. The control effect is based on variation of the dielectric constants ε by the control voltage. Figure 19 illustrates this. In the case of some dielectric substances hysteresis curves are obtained which are very similar to those for magnetic substances [11]. Thus, although there is no iron present here, a so-called ferro-electric effect is spoken of, in a similar way to that used in ferro-magnetism. This ferro-electric effect is due to the alignment of electric dipoles of ionized atoms in non-magnetic, crystalline substances.

The dielectrics used are barium titanate and some combinations of strontium titanates with barium titanates and also combinations of barium and lead zirconates. Unfortunately the dielectric constants of these substances are strongly affected by temperature so that a new dielectric is needed for each temperature range. A certain degree of temperature compensation can only be achieved by a combination of various dielectrics. The dielectric substances, like the magnetic ones, have a Curie point, the temperature of which is, however, much lower. The greatest amplification lies in the vicinity of the Curie point; it is specially important therefore to keep the dielectric at this temperature. For this reason the temperature of dielectric amplifiers is often regulated thermostatically. The non-linear dielectric of the condenser acts as the temperative sensitive member of the thermostat. Such an arrangement is not necessary in the case of magnetic amplifiers.

Figure 20 shows the typical circuit of a dielectric amplifier. Two non-linear and two linear condensers are connected to form a bridge. The control potential is connected in one diagonal arm of this bridge and the supply potential with the load resistance R_A in the other. The linear condensers have the function of rendering the circuit symmetrical; naturally they reduce the amplification. The source for the supply potential is provided in most cases by a low-power electron-tube generator. The characteristic curves of dielectric amplifiers are similar to those of magnetic amplifiers. The maximum degree of power amplification is also approximately 1 : 100,000 for each stage. In contrast to the magnetic amplifier, the dielectric amplifier permits the amplification of vastly higher frequencies (up to 10 Mc/s). The magnetic amplifier is a low-resistance current amplifier whereas the dielectric one represents a high-resistance voltage amplifier.

Practical application of the dielectric amplifier has not yet been achieved because the development, particularly of dielectrics, is still in too fluid a state. Because of the character of the dielectric amplifier as a valve-less high-frequency amplifier it has been proposed to use it in radio sets with a corresponding reduction in the number of electronic valves.

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G_E input quantity
G_H auxiliary quantity (e.g. source of energy)
G_A output quantity.

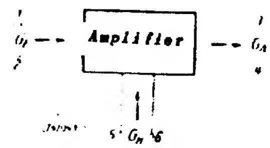


Fig.1: Diagram of an amplifier. Relation of energies: $G_H > G_A > G_E$. The numbers of the terminals have the same significance in the subsequent figures.

G_E field potential
G_H energy of rotation
G_A terminal voltage.

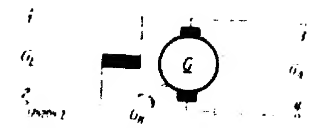


Fig.2: Basic circuit of the machine amplifier (separately excited D.C. generator).

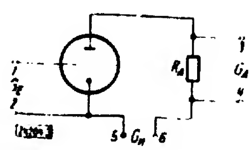


Fig.3: Electronic amplifier

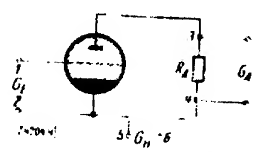


Fig.4: Thyratron or Mercury Vapour Rectifier

Figs. 3 and 4: Basic circuit for amplifiers with charge carriers. G_E grid voltage. G_H anode voltage. G_A output power across the working resistance R_A.

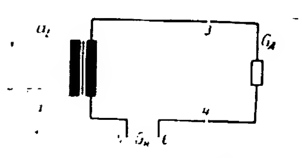


Fig.5: Magnetic amplifier.
G_E control current
G_H alternating voltage
G_A output current in the working resistance R_A.
a - choke for suppression of A.C. voltage induced by G_A.

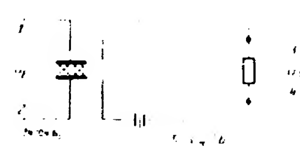
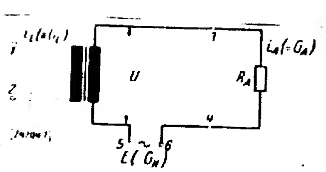


Fig.6: Capacitative amplifier.
G_E control voltage
G_H alternating voltage
G_A output voltage across the output resistance R_A.

Figs. 5 and 6: Basic circuits of amplifiers based on variation of an A.C. resistance.



E source of alternating voltage
I_A output A.C.
I_E control D.C.
R_A working resistance (load)
U alternating voltage across the choke coil.

Fig.7: Currents and voltages in the magnetic amplifier shown in Fig. 5.

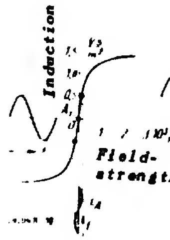


Fig.8

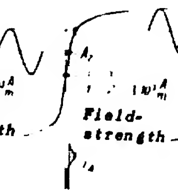


Fig.9

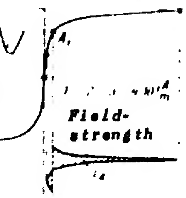


Fig.10

Fig.8: Formation of a sinusoidal current i_A. Control current $i_E = 0$. The characteristic curve $B = f(H)$ is rectilinear in the section under consideration (working point A_1). The working point can (by reversing the polarity of i_E) be transposed to the negative branch of the curve; this also applies to Figs. 9 and 10.

Fig.9: Formation of an amplified, somewhat distorted current i_E. The control current i_E is no longer zero. Working point A_2 is already in the non-linear section of the curve.

Fig.10: Formation of a considerably amplified and distorted current i_E. The control current i_E is large and carries the working point A_3 into the pronounced bend of the curve.

Figs. 8 to 10: Method of operation of the magnetic amplifier. $1\ Vs/m^2 = 10^{-4}\ Vs/cm^2 = 10{,}000\ G$; $1\ A/m = 10^{-2}\ A/cm$.

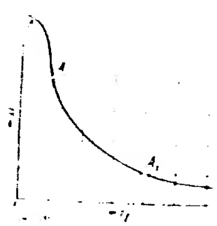
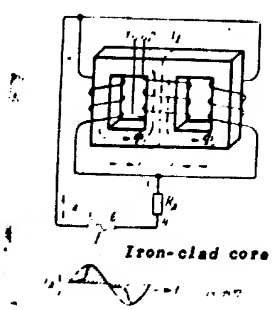
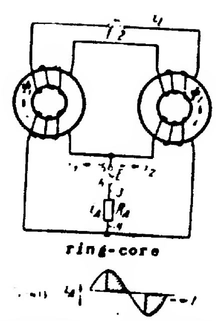


Fig.11: Relation of the permeability μ and hence the self-induction L to the control current i_E.





Figs. 12 and 13: Construction design of amplifiers with iron-clad and annular cores.

Below: Qualitative behaviour of the current i_A as a function of time t.

Φ_1 and Φ_2 magnetic fluxes.

$i_1 + i_2 = i_A$ partial currents.

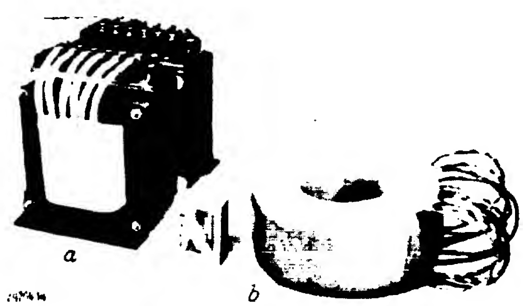


Fig.14: 300 VA commerical type amplifiers

a - iron-clad core of transformer laminations IV, $\mu_{max} = 250$.

b - ring-core of highly permeable sheet, $\mu_{max} = 100{,}000$.

Figs. 12 to 14. Single-phase magnetic amplifiers.

...regulator with a magnetic amplifier.

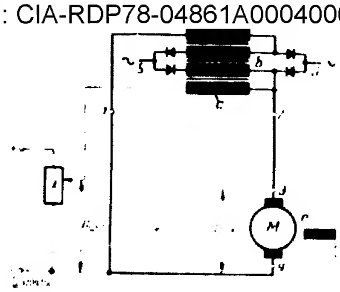
a - rotation speed adjustment (potential divider)

b - magnetic amplifier with feed-back coupling and D.C. output.

c - control coil.

d - compounding (feed-back) coil.

e - D.C. shunt-wound motor.



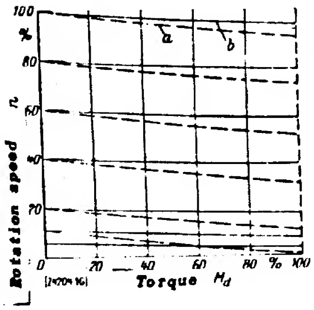


Fig.16: Rotation speed n as a function of the torque M_d in a D.C. shunt-wound motor.

a - characteristic curves for the motor without speed regulation.

b - the same with a regulation circuit as shown in Fig.15.

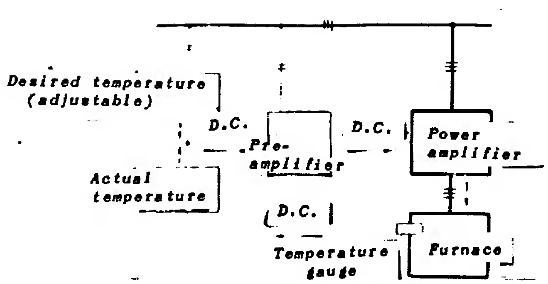


Fig.17: Circuit diagram of a magnetic amplifier for regulating an electrical industrial resistance furnace.

Heavy lines - three phase mains.
Light lines - alternating or direct circuits.

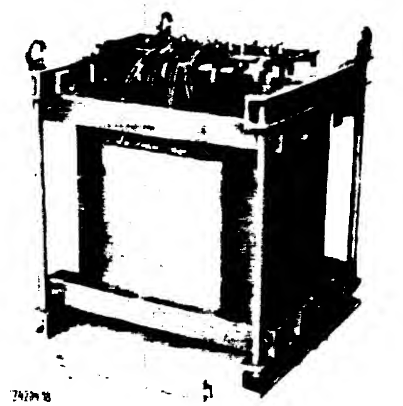


Fig.18: 16 KVA three-phase magnetic amplifier (see Fig.17).

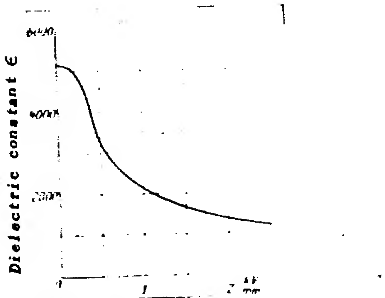


Fig.19: Dielectric constant ε of barium titanate (11) as a function of the condenser field E (control characteristic curve).

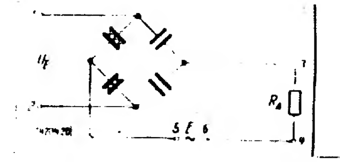


Fig.20: Basic circuit diagram of a capacitative amplifier.